SOME EVIDENCE REGARDING THE KIND AND QUANTITY
OF SEDIMENT TRANSPORTED BY
DENSITY CURRENTS

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structure; (2) reduce the downstream sediment-carrying capacity to a minimum; (3) choose a site with bed and banks of the most stable materials, or increase particle-stability artificially; (4) produce a stable flow-pattern with optimum eddy-orientation and minimum eddy-intensity; (5) reduce flow-velocities to the minimum; and (6) apply each of the first five principles with due regard for the others.

The first five principles have been suggested in direct recognition of the five scour-control factors, respectively. The sixth principle is stated in recognition of the impossibility of applying the preceding five independently. It must be recognized also that one or more of the principles may be inapplicable to a given situation because of inconsistency of that phase of scour-control with the purpose for which the structure is to be built.

The writer has set down certain generalities on scour-control because he believes they may be valuable in directing further research in scour-control, in guiding the location and design of structures, and in analyzing the performance of existing structures. Obviously, the nature of the material he has presented establishes the debt the writer owes to others studying and writing in the field of scour-control. The references cited below have been of particular value to him in formulating his analyses.

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Introduction

Density-currents are of major importance as transporting and sorting agents for fine sediment. Under unusual or extreme conditions they have a part in the distribution of surprisingly coarse material. The magnitude of the work they perform in sedimentation may have been obscured somewhat in recent years because there has been a tendency to think of density-currents almost solely as turbid underflows in bodies of still water, especially in reservoirs that are fed by muddy rivers. Density-currents are not limited to underflows, be they turbid or otherwise. Their occurrence is confined neither to reservoirs in particular nor to bodies of water in general. For example, dust storms usually are true density-currents [see 1 of "References" at end of paper]. The importance of the atmosphere as a transporting and sorting agent is well known, and has been demonstrated clearly by evidence gathered by JOHAN AUGUST UDDEN [2], EDWARD ELWAY FREE [3], and many others. The fact that needs wider recognition is that the atmospheric transportation of sediment is accomplished very largely by density-currents.

Although some quantitative data are available as to the kind of sediment transported by density-currents, they are too few to justify conclusions other than tentative ones. As to the volume of sediment transported, there is apparently a complete absence of quantitative data, although a large body of excellent qualitative data has been obtained since 1935 by the United States Bureau of Reclamation at Lake Mead [4], and some valuable information has been gathered by the United States Soil Conservation Service at Lake Issaqueena, near Clemson, South Carolina [5]. With these conspicuous exceptions present-day estimates as to the quantity of sediment transported by density-currents must be based upon evidence that is as incomplete, inadequate, indirect and, scientifically, as unsatisfactory as that available to UDDEN nearly a half century ago. Meanwhile, methods of making mechanical analyses of sediments have been simplified and vastly improved [6], and new sampling techniques and instruments have been developed for use in investigating sediment suspended by water [7]. Since FREE pointed out the inadequacies prevalent in 1911, little, if any, progress has been made in the technique or the equipment for accomplishing the much more difficult task of obtaining true samples of sediment suspended in the atmosphere [8].

If the present paper does no more than make evident the need for more and better data, it will have served a worthy purpose.

The Quantity of Sediment Transported by Density-Currents

Data are available upon which to base a reasonably dependable estimate as to the quantity of sediment transported by turbid underflows at Lake Mead since storage began on February 1, 1935. For the first 15 months of storage, water was released through a diversion-tunnel at approximately the normal low-water level of the Colorado River. This discharge normally was clear but at least four times during 1935 it became very muddy although the surface water in the reservoir remained clear. This indicated that turbid underflows were reaching the dam. NATHAN C. GROVER and CHARLES S. HOWARD estimated that as much as 6,000,000 tons of fine sediment, brought by density-currents into lower Lake Mead, was discharged through the tunnel-outlets during the 35 days of turbid outflow in 1935 [9]. Had this sediment remained in the reservoir and reached a concentration of 60 pounds dry weight per cubic foot, it would have occupied 4,600 acre-feet of storage space. Volumetrically this is a conservative estimate. Fine sediment, deposited under water and not subjected to compaction by exposure to the air, may have a concentration of less than 30 pounds per cubic foot.

Since May 1, 1935, withdrawals have been made through towers at levels 250 and 400 feet higher than that of the tunnel-outlet. No turbid water has been discharged and, therefore, all sediment transported by density-currents has been retained within the reservoir where it has formed a submerged lake of mud that extends upstream for approximately 40 miles. It is possible to estimate the quantity of sediment in this lake by using measurements of sediment-concentration and depth obtained by the Bureau of Reclamation in conjunction with data contained in the original capacity-table prepared by the Soil Conservation Service [10]. Calculated upon this basis the mean daily rate of sediment-accumulation in the submerged lake appears to have been about 135,000 tons, or slightly more than 100 acre-feet at 60 pounds per cubic foot, for the period from May 1, 1936, to December 1, 1941. This is approximately seven times the rate of sediment-discharge as calculated by GROVER and HOWARD for 11 months of 1935.

Although density-currents probably play an important part in the transportation of fine sediment whenever muddy streams enter bodies of still water, their activity is not limited to such circumstances. Waves stir up sediment along shores and on sufficiently shallow bottoms during storms, and the suspensions of fine particles created in this manner become density-currents if there are bottom slopes down which they may move. Thus the fine-grained portion of the sediment, because it remains in suspension longer, is carried away into deeper water, but the coarser portion is redeposited very promptly. The coarsest constituents may not be thrown into suspension at all. Usually it is assumed that sorting and transportation can take place under such circumstances only if currents exist at the time the suspensions are created [11]. This view fails to recognize the fact that if a sloping bottom is present, suspensions are very apt to become turbid underflows. Perhaps seismic disturbances create other suspensions at depths that are never reached by even the most violent storm-waves. It seems entirely possible that the total volume of the sediment transported by aqueous density-currents surpasses that of the sediment carried to the oceans by all the rivers of the world.

Major dust-storms involve from a few hundred to more than a million cubic miles of atmosphere [12]. From evidence UDDEN had available for 32 dust-storms, he calculated that the load of suspended sediment ranged from 160 to 126,000 tons per cubic mile of turbid atmosphere [13]. If the latter figure seems unreasonable it is well to remember that if the suspended particles have a mean density of 2.2 and the sediment-concentration is 1 part per 100,000 by volume, the dust-load will be approximately 100,000 tons per cubic mile.

Such evidence as has been gathered during the present century does not indicate that UDDEN'S estimates should be rejected. A dust-storm that originated west of the Mississippi River passed over Washington, D. C., early in May 1934. Visibility was reduced to half a mile. From data gathered over Washington it was estimated that the dusty air-mass contained approximately 100 tons of sediment per cubic mile [14]. This is equivalent to 20 parts per million (ppm) by weight, but only to 0.01 ppm by volume.

On June 5, 1939, a Japanese dust-storm covered 75,000 acres of valuable farm-land on Hokkaido Island with an inch of fine sediment [15]. Assuming that this fresh deposit had a density in situ of 1.3, it weighed approximately 10,000,000 tons. This would be equal to the total sediment-load from 10,000 cubic miles of atmosphere in which the sediment-concentration was ten times as great as in the Washington storm. It seems probable, therefore, that the concentration was actually very much greater than the suggested value--greater, perhaps, than the highest estimate made by UDDEN.

In March 1918 a storm scattered dust from Iowa to Maine. It was estimated to have deposited 13.5 tons of sediment per square mile at Madison, Wisconsin [16]. On Hokkaido Island the figure was probably not far from 85,000 tons per square mile. In some of the famous falls of sirocco dust in Europe the data indicate deposits of as much as 30 grams per square meter [17]. On Hokkaido it was approximately 30,000 grams per square meter. It is of interest that the Monthly Weather Review comments that the Japanese storm was one "rivaling those of the United States' Dust Bowl" [18].

Baca County, Colorado, lies near the center of an enormous dust-bowl that includes areas in Colorado, Nebraska, Kansas, Oklahoma, Texas, and New Mexico. During 1936 Baca County experienced dust-storms in which pedestrians collided with one another because visibility was reduced to zero. Highway travel was paralyzed, and lighted display-windows were not visible from a distance of 40 feet. Aviators reported dust at altitudes of 15,000 to 20,000 feet [19]. The frequency of dust-storms in that area is shown by the records of the United States Weather Bureau at Amarillo, Texas. Between January 18, 1933, and February 26, 1936, this station recorded 192 such storms. In 24 of these visibility was reduced to less than 500 feet, and in 35 others to less than half a mile. Although seven storms continued for 50 hours or longer, the average duration for the entire series was ten hours.

Since World War I practically all top-soil has been stripped by atmospheric density-currents from several thousand square miles in this particular dust-bowl, and from 25 to 75 per cent has been blown from a much greater area [20]. The total volume removed during the last quarter-century from this and other American dust-bowls will never be known, but it probably should be measured in cubic miles rather than in millions of tons or thousands of acre-feet.

Since the days of the poet HOMER, falls of dust have been recorded in Europe [21]. From meteorological evidence it has been demonstrated that this dust comes from the Sahara, and there is every reason for believing that that great sandy waste is the result of prolonged degradation by wind. The sand that remains is too coarse to be readily transported by atmospheric density-currents. According to FREE, an average of more than 5-1/2 inches of material from the desert has been deposited over much of Europe by dust-storms in the three thousand odd years during which there is authentic historic evidence of their occurrence [22]. This statement has been given wide circulation in scientific literature. By referring to the data submitted as a basis for this estimate, it will be seen that two unfortunate arithmetical errors have resulted in a final figure that is 100-fold too high. FREE'S estimate seems reasonable, and may be a good one; it is not supported, however, by the data he submits.

CHARLES ROLLIN KEYES estimates that 0.01 inch of sediment is deposited annually by dust-storms along the Missouri River [23], and BOHUMIL SHIMEK gives one mm as the rate of accumulation of Mississippi Valley loess [24]. It will be noted that these rates are roughly five and 20 times as great as FREE'S estimate for sirocco dust in Europe. FREE arrived at a figure of not less than one inch per century as the rate of accumulation of wind-borne dust in the Mississippi Valley [25]. This estimate is based upon the statement that about 0.02 inch was deposited at Rockville, Indiana, during a storm in January 1895. In the light of the known frequent occurrence of dust-storms over the States west of the Mississippi, FREE suggests 0.01 inch as a reasonable estimate of the mean annual deposit. But FREE also states that the dust deposited at Rockville amounted to 1.50 grams per square meter. If it is assumed that the density of this dust was 1.5 (a figure frequently used in Europe for such deposits) then there was one cubic centimeter per square meter. If, however, the deposit was 0.02 inch thick there should have been more than 500 cubic centimeters per square meter, with a total weight of 760 grams. It would seem probable that of the two types of data submitted, those based upon weight would be more acceptable than those based on depth-measurements. Had FREE used the weight, instead of the depth-measurement, and reduced this by 50 per cent as he did the depth-measurement, he would have been forced to conclude that the rate of deposition was such that 50,000 years would be required to produce a deposit one inch thick. In spite of this, the events of the last quarter-century make FREE'S estimate appear to be better than the data submitted to support it.

Evidence of dust-storms of the past is to be had in loess-deposits, the greatest of which are to be found in China where beds occasionally reach a thickness of several hundred feet. The vast loess-deposits that cover tens of thousands of square miles of the Mississippi Valley probably had their origin in the exposed Cretaceous and Tertiary formations found on the High Plains from Wyoming to Texas [26, 27], and in the outwash of recent glacial periods [28].

It is known that "gravity winds" of great violence sweep down from the icy plateaus of Greenland and Antarctica, and that they lose their high velocities and die out rather rapidly as they flow out over the open sea [29]. Such winds owe their comparatively high density to the fact that they are much colder and drier than the atmosphere at the margins of the ice-caps. Unquestionably they are density-currents. It is reasonable to believe that similar winds characterized periods of glaciation in the Mississippi Valley and that they entrained large quantities of rock-flour and other fine debris which were deposited, at no great distance, as loess.

Volcanoes are the greatest single source of atmospheric dust. A fact that is not generally recognized is that the winds that accompany violent volcanic activity often are density-currents that are produced more or less completely by the very sediment they transport. They are, therefore, turbid underflows in the strictest sense. One of PLINY'S letters contains a vivid eye-witness account of the dust-clouds that were produced by Vesuvius when Pompeii was destroyed in 79 A.D. [30].

Various students have estimated that in its eruption of 1815 Tomboro ejected 32, 50, or 92 cubic miles of dust that was scattered over an area of 6,000,000 square miles [31, 32, 33]. This eruption, like that of Krakatao in 1883, produced rather coarse deposits several inches deep at a distance of 1,000 miles [34]. In his report to the Dutch Government on the eruption of Krakatao, R. D. M. VERBEEK estimated that 4.3 cubic miles of material was thrown out, and that about one-third fell at a distance of more than 15 km from the volcano [35]. This dust is said to have settled all over the world. FREE has assembled data on a large number of eruptions in various parts of the world, and cites many instances of volcanic dust being carried by the atmosphere from 100 to 1500 miles and deposited in layers of appreciable thickness [36]. According to estimates by N. S. SHALER, approximately 600 cubic miles of fine material was ejected from the world's volcanoes in the century and a half between 1770 and 1920, and a very large percentage of this was of sizes that could be readily transported by the atmosphere [37].

The evidence that has been presented in the foregoing paragraphs is a fair sample of the kind of information that is available. It is obvious that more basic facts, particularly quantitative data, are needed before the importance of density-currents as transporting agents can be evaluated accurately. There can be no doubt, however, that their role is a major one.

The Kind of Sediment Transported by Density-Currents

UDDEN concluded, after considerable study of windblown dust from many sources and some experimentation, that ordinary strong winds do not transport in suspension readily quartz particles that are larger than 0.1 mm in diameter [38]. According to JOHANNES WALTHER particles about two mm in diameter can be transported by the wind, but not held in suspension, and gravel the size of peas rarely may be carried along [39]. FREE states that R. W. PUMPELLY, GERHARD

Table 1--Mechanical analyses of dustfalls, loess, and bottom-deposits

<table>
<tr><th rowspan="2">No.</th><th>Clay</th><th colspan="2">Silt</th><th>Sand</th><th rowspan="2">Remarks</th></tr>
<tr><th><5µ</th><th>5µ-20µ,</th><th>20µ-50µ</th><th>>50µ</th></tr>
<tr><td></td><td colspan="4">Per cent by weight</td><td></td></tr>
<tr><td>1</td><td>24.2</td><td colspan="2">72.6</td><td>3.2</td><td>Average for samples from five American dustfalls</td></tr>
<tr><td>2</td><td>33.4</td><td colspan="2">64.0</td><td>2.6</td><td>Dustfall, New Hampshire and Vermont, February 24, 1936 [41]</td></tr>
<tr><td>3</td><td>25.6</td><td colspan="2">68.4</td><td>6.0</td><td>Dustfall, Madison, Wisconsin, March 19. 1920 [42]</td></tr>
<tr><td>4</td><td>32.0</td><td colspan="2">56.4</td><td>11.5</td><td>Loess, Grundy County, Missouri [42]</td></tr>
<tr><td>5</td><td>24.5</td><td colspan="2">66.5</td><td>9.0</td><td>Loess, Muscatine County, Iowa [42]</td></tr>
<tr><td>6</td><td>10.5</td><td colspan="2">42.3</td><td>47.2</td><td>Loess, North Platte, Nebraska [42]</td></tr>
<tr><td>7</td><td>74.1</td><td>23.9</td><td>2.0</td><td>none</td><td>Bottom-deposits, Lake Mead, mean values for 81 samples within 30 miles of Boulder Dam, January 1938 to July 1940; dispersed with sodium oxalate [4]</td></tr>
<tr><td>8</td><td>1.3</td><td>95.4</td><td>3.3</td><td>trace</td><td>Bottom-deposits, Lake Mead, mean values for 133 samples, as above, but not chemically dispersed [4]</td></tr>
<tr><td>9a</td><td>67.0</td><td>24.2</td><td>8.8</td><td>trace</td><td rowspan="2">Bottom-deposits, Lake Arthur Reservoir, 3,000 feet from Dam; original samples contained nine per cent by weight soluble and organic matter [43]</td></tr>
<tr><td>9b</td><td>67.0</td><td>27.5</td><td>5.5</td><td>trace</td></tr>
<tr><td>10</td><td>77.4</td><td colspan="2">22.6</td><td>trace</td><td>Sediment discharged through valves, Lake Arthur; sample contained 7 per cent soluble and organic matter [43]</td></tr>
<tr><td>11</td><td>78.7</td><td>19.3</td><td>1.5</td><td>0.5</td><td>Bottom-deposits, Lake Issaqueena, mean values for three samples within 2200 feet of Dam [5]</td></tr>
</table>

ROHLFS, and N. M. PRZHEVALSKII have seen stones from two inches in diameter to as large as the fist blown along in Turkestan, the Sahara and Gobi deserts, respectively [40].

In this paper interest is centered in suspended load. Mechanical analyses indicate that atmospheric currents transport material coarser than that ordinarily carried by aqueous underflows, and that, unless volcanic activity is involved, under all but extreme conditions the sediments transported by density-currents contain little or no material that is more than 0.1 mm in diameter. Almost invariably these sediments are very well sorted.

In a series of samples from five American dust-falls approximately 76 per cent of the sediment was coarser than five microns, and individual samples contained from 2.6 to 6 per cent of sediment coarser than 50 microns (Table 1, Nos. 1, 2, and 3). Loess, apparently, contains a higher percentage of coarser material (Table 1, Nos. 4, 5, and 6). In a series of 81 bottom-samples obtained at Lake Mead within 30 miles of Boulder Dam, only 26 per cent of the sediment was coarser than five microns, and particles coarser than 50 microns were ordinarily not present in individual samples (Table 1, No. 7). Samples were obtained during a period of 30 months extending from January, 1938, to July, 1940, and were dispersed with sodium oxalate before analyses were made.

Although Lake Mead was approximately 100 miles long when the samples were taken, the sediment size-distribution is remarkably like that found at Lake Arthur which is only six miles long (Table 1, Nos. 9 and 10), and at Lake Issaqueena which is less than 1.5 miles long (No. 11). The mean bottom-slope at Lake Mead is five feet per mile, at Lake Arthur it is 15, and at Lake Issaqueena it is nearly 23. Since the coarseness of the sediment that can be transported in suspension is greatly influenced by the velocity of the stream, it might be assumed, therefore, that density-current velocities are essentially the same at the three reservoirs, regardless of the considerable difference in bottom-slopes. Field-observations, however, do not support this assumption but indicate that velocities are highest at Lake Mead, and lowest at Lake Issaqueena.

Sediments transported by density-currents at Lake Mead and Lake Arthur are rather highly flocculated. Because flocculation tends to increase the effective settling-velocity of suspended particles, higher stream-velocities are needed to keep particles of a particular size in suspension when they are flocculated than when they are not. By comparing the data in Table 1, No. 7, with that in No. 8 it will be seen that although approximately 74 per cent of the sediment in lower Lake Mead is actually less than five microns in diameter, flocculation causes nearly 99 per cent of it to settle as if it were more than five microns in diameter.

It is evident, then, that higher density-current velocities are needed to transport the flocculated sediment at Lake Mead than are necessary at Lake Issaqueena where flocculation is negligible. The velocity of a density-current is influenced principally by the bottom-slope, the depth of flow, and the magnitude of the difference in density between the two fluids involved. Very little is known about the depth of flow at the three reservoirs but it is certain that the density-difference is much greater at both Lake Mead and Lake Arthur than at Lake Issaqueena, and this factor alone may increase velocities sufficiently to offset the effect of flocculation.

Santa Anita Reservoir, in the San Gabriel Mountains, near Arcadia, California, is approximately half a mile in length and has a mean bottom-slope in excess of 300 feet per mile. During the great storm of March 1938 an underflow of sediment and debris reached the dam and succeeded in clogging two outlets that were operating and fully open [44]. One of these outlets is located 21 feet above the other. Before the storm the bottom outlet was 17 feet above the sediment-level. After the storm the top outlet was 17 feet below the sediment-level. The fresh bottom-deposits near the dam were composed of silt, sand, and gravel in which were embedded bits of household equipment that had been in cabins in the canyon above the reservoir prior to the storm. Slopes similar to or greater than that at Santa Anita are not uncommon in the oceans. Wave-action during violent storms, may create suspensions that include rather coarse sand and, on such slopes, these suspensions may flow as density-currents. Evidence that they do is probably already available in the rapidly growing body of data on marine sediments.

Density-currents that result from volcanic activity transport relatively coarse material because of the method of entrainment of the sediment, and because high sediment-concentrations are frequently present on steep slopes. FRANK A. PERRET observed a nuée ardente at Mt. Pelée that had a mean velocity of 96 miles per hour for a distance of four miles [45]. His observations indicate that large blocks of lava may be carried as bed-load on steep slopes.

In 1898 UDDEN published a mechanical analysis of volcanic dust that fell in Norway more than 600 miles from its point of origin in Iceland [46]. Only a fraction of one per cent of this sediment was finer than 16 microns, about ten per cent was coarser than 125 microns, and practically none of it was larger than 250 microns. The almost complete absence of particles finer than 16 microns may indicate that the material had been ejected to heights from which such fine particles were unable to return to Earth in the time required for the sediment-laden air-mass to travel from Iceland to Norway.

Conclusion

Evidence now available shows clearly that both aqueous and atmospheric density-currents can and do transport enormous quantities of fine sediment, but data are not adequate for making other than very rough estimates of the total volume of sediment moved in this manner. Material deposited by density-currents is almost invariably well sorted, and apparently, atmospheric deposits are considerably coarser than aqueous ones.

The need for data like those gathered at Lake Mead is greater than it has ever been. The problems that such information may help to solve are not all academic ones that have to do with the size or the sorting of sediments, or the origin of loess. Density-currents rob one area of its soil, bury crops on others, disrupt the machinery of transportation, and confront the nation with problems in the fields of economics, sociology, and health. Aqueous density-currents distribute sediment that occupies valuable space in reservoirs, lakes, and harbors--space, incidentally, that increases in importance as the nation becomes more and more dependent upon it. For these, and many other reasons, it is desirable to obtain a more thorough knowledge of them.

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